Coherent interannual and decadal variations in the atmosphere-ocean system

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[1] We investigate the source of poleward propagating atmospheric zonal wind anomalies, originating at the equator and penetrating to high latitudes in both hemispheres in conjunction with ENSO [*Dickey et al.*, 1992], and report the discovery of similar variability on decadal and longer timescales. Since atmospheric dissipation times are generally on the order of a month or less, we examine the ocean as a "memory" source for these globally coherent anomalies. This hypothesis is substantiated by the observation of complementary oscillation in the sea surface temperature (SST) field; further, we detect a robust decadal variability (~10–12 yrs) in both the SST and contemporaneous atmospheric angular momentum (AAM) series. Analyzing GISST SST data beginning in 1902, we confirm this decadal mode and find signatures of longer (multidecadal) SST variability centered in the equatorial and North Pacific. *INDEX TERMS:* 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 4215 Oceanography: General: Climate and interannual variability (3309); 4522 Oceanography: Physical: El Niño. **Citation:** Dickey, J. O., S. L. Marcus, and O. de Viron, Coherent interannual and decadal variations in the atmosphere-ocean system, *Geophys. Res. Lett.*, *30*(11), 1573, doi:10.1029/2002GL016763, 2003.

1. Introduction

[2] Interannual-decadal fluctuations in the Earth system have recently become a subject of intense interest in the geophysical community. Meridional heat transport by the ocean plays a central role in climate on these time scales, but limitations in observational data, modeling and dynamic analysis have prevented a complete understanding of the nature and origins of its variability [*Jayne and Marotzke*, 2001]. A number of recent studies have documented coupled ocean-atmosphere modes, which may link climate anomalies in low and high latitudes on interannual-decadal time scales [e.g., *Talley*, 1999; *Giese and Carton*, 1999]. On interannual time scales, climatic anomalies are dominated by the El Nino/Southern Oscillation (ENSO), a coupled ocean-atmosphere instability which originates in the tropical Pacific but has a global impact [e.g., *Glantz et al.*, 1991], and serves to export excess heat from the tropics to higher latitudes [e.g., *Sun and Trenberth*, 1998]. Concomitant changes in oceanic heat storage and surface temperature gradients can impact conditions at higher latitudes [e.g., *Jacobs et al.*, 1994], as well as sea-ice dynamics in both the northern [*Gloersen*, 1995; *Rind et al.*, 2001] and southern [*Peterson and White*, 1998; *Kwok and Comiso*, 2002] extratropics.

[3] Coherent interannual variations of the global atmosphere have been detected through analyses of zonally- and vertically-averaged zonal wind by applying temporal and spectral filtering techniques to isolate the meridional structure and propagation of anomalies in the axial component of atmospheric angular momentum (AAM) [*Dickey et al.*, 1992, 1999]. The resulting Hovmoeller diagrams (Figure 1) show striking evidence of coherent, global-scale propagation of AAM anomalies on interannual time scales, linked to the ENSO cycle. Westerly wind anomalies originate on the equator about 1–2 years in advance of major ENSO events and propagate towards the sub-tropics, where they intensify during the mature phase of ENSO. By contrast, easterly anomalies originate at the equator during the mature phase, signaling the return of strengthening trade winds and normal conditions to the tropics. The easterly anomalies propagate towards the sub-tropics, where they lead to a weakening jet stream during the cool (La Nina) phase. AAM anomalies of both signs subsequently propagate polewards from the sub-tropics in both hemispheres, with decreased intensity at high latitudes, where they lag behind the main events of the ENSO cycle by about four years. These fluctuations are bimodal, containing both low frequency (LF) and quasi-biennial (QB) components [*Barnett*, 1991], and attain their maximum amplitudes over the north and south Pacific [*Black et al.*, 1996]. The robustness of poleward AAM propagation has been verified by analysis of nine GCM simulations incorporating observed SST data [*Marcus and Dickey*, 1994], performed as part of the Atmospheric Model Intercomparison Project [*Gates*, 1992] for the decade 1979–1988, and by analysis of NCEP reanalysis data for the period 1958–1998 [*Dickey et al.*, 1999].

[4] What is the origin of these long-lived circulation anomalies? Since atmospheric dissipation times are generally on the order of a month or less, the "memory" associated with these slowly propagating signals must reside elsewhere in the climate system. In view of their ENSO connection, the most likely mechanism involves atmospheric coupling to the associated large-scale SST anomalies. To investigate this thesis, we analyzed monthly

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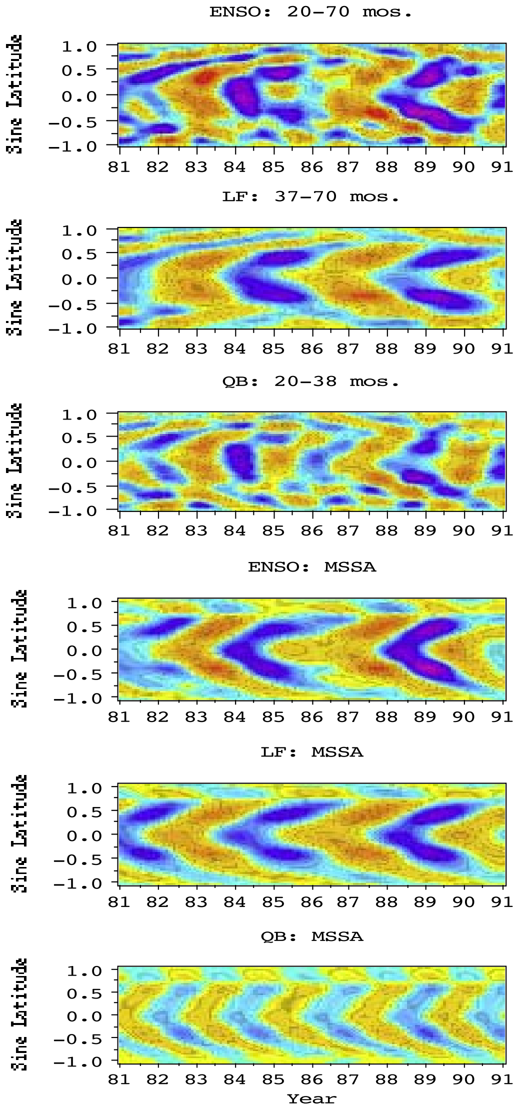

Figure 1. Latitude-time plots of atmospheric angular momentum (AAM) variations [*Kalnay et al.*, 1996] computed for 23 equal-area latitude belts, considering winds up to 100 hPa. The recursive filtering [*Murakami*, 1979] isolates the full ENSO band (20–70 months), and its low-frequency (LF, 37–70 month), and quasi-biennial (QB, 20–38 month) components [panels 1–3]. The M-SSA [*Moron et al.*, 1998] technique was applied with the LF and QB modes emerging as the leading pairs (bottom two panels), the full ENSO mode (4th panel) being the sum of these modes. Warm colors denote positive (westerly) AAM anomalies associated with the warm (El Nino) phase (1982–83 and 1986–87); cold colors denote easterly anomalies associated with the cold (La Nina) phase (1988–89 event).

satellite SST anomaly data [*Smith and Reynolds*, 1998], as well as those inferred from the GISST data set.

2. Data Analysis

[5] We explore the relation between global anomalies in zonal wind speed and the evolution of SST anomalies in the Pacific basin, where the ENSO signal is the strongest and where the largest "heat reservoir" of the climate system is located. The SST, therefore, was analyzed in conjunction with simultaneous AAM data, covering the period 1982–1998. The AAM data were zonally averaged in 10 equal-area latitude belts around the globe, while the SST data were zonally averaged in 10 equal-area latitude belts covering the Pacific only. The data are analyzed using the powerful technique of Multichannel Singular Spectrum Analysis (M-SSA) [*Vautard and Ghil*, 1989], which identifies modes of joint variability among the input data "channels", based on the eigenvector decomposition of the autocorrelation matrix of the signal. Oscillatory modes are characterized in M-SSA by paired eigenvalues, whose principal components (i.e., time coefficients) are in approximate quadrature with each other. To avoid the dominance of variability in one or several channels, all of them are normalized, such that the standard deviation of every channel is one. This also allows the combined analysis of different types of data, as SST and AAM. We also performed M-SSA on SST variations alone using the longer GISST data spanning the years 1902–1998 and zonally averaged in 20 equal-area latitude belts covering the Pacific basin, to test the robustness of the decadal mode.

3. Results

[6] As shown in Figure 2 and listed in Table 1, the first three modes or pairs (listed in order of their contribution to

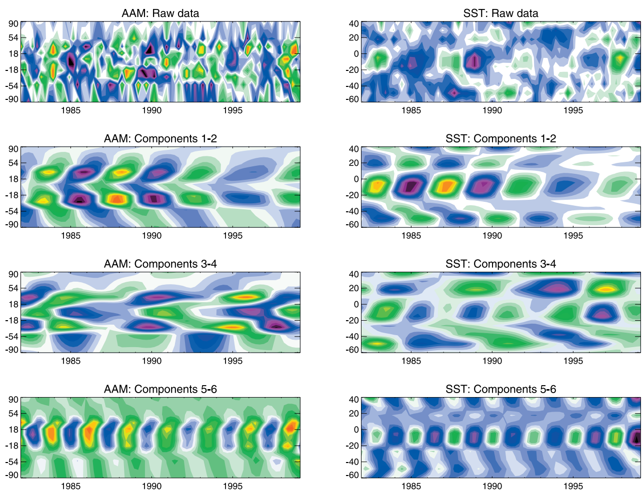

Figure 2. Latitude-time (Hovmoeller) plots of atmospheric angular momentum (AAM, left column) and sea surface temperature (SST, right column) variations. We use the NCEP reanalysis series integrated over 10 global equal-area latitude belts for AAM, while the SST obtained from the CDC is computed for 10 equal-area latitude belts for the Pacific only. The first, second, third and fourth row entries display, respectively, the raw data of each; the first reconstructed oscillatory pair, comprising the low-frequency ENSO component; nearly decadal pairs; and the quasi-biennial pair. Note that these pairs result from multi-channel singular spectrum analysis (M-SSA) performed jointly on AAM and SST.

Table 1. Interannual-Decadal Variability Estimated From SST [*Smith and Reynolds*, 1998] and AAM [*Kalnay et al.*, 1996] Data (1982–1998)

M-SSA Pairs	AAM & SST (years)	AAM (years)	SST (years)
Pair 1 (1st and 2nd components)	LF ~ 4.5	LF ~ 4.5	Decadal ~ 10
Pair 2 (3rd and 4th components)	Decadal ~ 10	QBO ~ 2.3	LF ~ 4.5
Pair 3 (5th and 6th components)	QBO ~ 2.3	Decadal ~ 10	QBO ~ 2.3

the joint AAM/SST variability) resulting from the 20-channel M-SSA computation applied jointly to the AAM/SST data are mostly poleward propagating anomalies at the LF (~4.5 yr), decadal (~10 yr), and QB (~2.3 yr) time scales. The LF and QB modes were previously identified in AAM propagation [*Dickey et al.*, 1992], while decadal and longer time scales were seen as a modulation of these modes [*Dickey et al.*, 1999], and have also been identified in recent studies of oceanic variability [e.g., *Chao et al.*, 2000]. On LF and decadal time scales, the AAM shows robust poleward propagation to high latitudes in both hemispheres (Figure 2), while the SST shows poleward propagation in the southern hemisphere and both propagating and standing oscillations in the northern hemisphere.

[7] To increase the robustness of our analysis, we performed two separate 10-channel M-SSA computations on the AAM and SST data, verifying that they produce similar modes (Table 1); note that the order is different, with the decadal-scale mode dominating the SST analysis, and the LF mode forming the leading pair for AAM. We also performed M-SSA on SST variations alone using the longer GISST data spanning the years 1902–1998; the results are summarized in Table 2. As seen in Figure 3, the first reconstructed pair shows a multi-decadal mode, with standing oscillations between the equatorial and north Pacific. The next two pairs show decadal and LF oscillations centered at the equator, containing both standing and propagating components. Strong interdecadal modulation is seen in the amplitude of these two modes, with poleward propagation especially evident in the LF band.

4. Discussion and Conclusions

[8] Two broad hypotheses concerning the mechanism responsible for maintaining these coupled AAM/SST signals against dissipation may be considered [e.g., *Goodman and Marshall*, 1999]:

[9] (1) The atmosphere responds passively to a changing SST field at its lower boundary, and plays little direct role in maintaining the SST signal. In this case, the observed meridional propagation of the SST pattern results from dynamical processes operating within the oceans themselves, as a delayed response or adjustment to interannual-decadal wind stress in the tropics via Rossby/Kelvin waves; if the forcing function has a long zonal wavelength and low frequency, in particular, propagation far from the equator can occur [e.g., *Philander*, 1990; *Qiu et al.*, 1997]. Processes involved in the poleward transport of oceanic sensible heat as part of the ENSO cycle [e.g., *Wyrtki*, 1985; *Jin*, 1997; *Sun*, 2000] would also fall into this category.

[10] (2) The atmosphere plays an active role in generating the coupled propagation patterns, by providing feedback to the ocean. The importance of atmospheric feedback on the tropical oceans has been well-established in studies of ENSO variability [e.g., *Neelin et al.*, 1998]; in addition, *Wang and Weisberg* [1998] have shown that coupling with the atmosphere allows interannual oceanic anomalies to propagate beyond the equatorial wave guide, to latitudes greatly exceeding the Rossby deformation radius. In the extratropics, upper oceanic heat storage and transport anomalies may be generated by wind-driven variations in upwelling, advection, mixing and evaporation [e.g., *Frankignoul*, 1985; *Liu*, 1993; *Talley*, 1999]. In particular, phase-locking between baroclinic Rossby waves in the ocean and resonant (i.e. quasi-stationary), equivalent-barotropic Rossby waves in the atmosphere may provide a positive feedback loop which helps to maintain the poleward-propagating disturbances against dissipation [e.g., *Goodman and Marshall*, 1999; *van der Avoird et al.*, 2002].

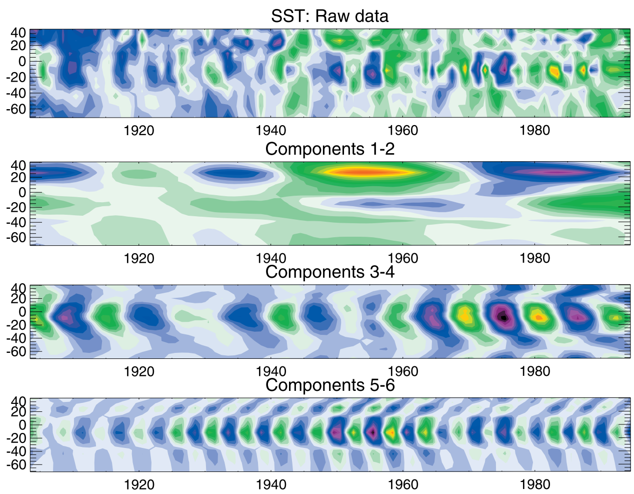

Figure 3. Latitude-time (Hovmoeller) plot of sea surface temperature (SST) variations from the GISST analysis. The raw data, zonally-averaged in 20 equal-area latitude belts for the Pacific, are displayed in the top panel; the first M-SSA pair, showing multidecadal variability, in the second panel; the second pair, with nearly decadal variability, in the next panel; the third pair, with a period of ~4–5 yrs, capturing the low-frequency (LF) ENSO component, in the bottom panel.

Table 2. Interannual-Decadal Variability Estimated From GISST Data (1902–1998)

M-SSA Pairs	SST (years)
Pair 1 (1st and 2nd components)	Multidecadal
Pair 2 (3rd and 4th components)	Decadal ~ 10
Pair 3 (5th and 6th components)	LF ~ 4.5

[11] Particularly striking in our results is the robustness of both the LF and decadal modes, which appear in the joint analysis of AAM and SST (first column of Table 1), in AAM and SST analyzed separately for the same period (second and third columns of Table 1), and in SST analyzed from the much longer GISST data set (Table 2). The detection of poleward-propagating LF signals in both global AAM and Pacific SST indicates that the observed meridional propagation of AAM results from non-stationary SST anomalies associated with ENSO variability. This conclusion is consistent with an earlier study [*Mo et al.*, 1997] employing the NCEP medium range forecast model. That study obtained realistic poleward-propagating AAM signals in an ensemble of experiments applying observed SST as a lower boundary condition; however, it failed to detect poleward atmospheric propagation in control experiments using either perpetual warm or cold ENSO conditions, or a standing SST oscillation between these two conditions, at the lower boundary.

[12] These results confirm our hypothesis concerning the ocean's role as a "memory" source for the coherent poleward propagation of interannual AAM anomalies, and serve to underscore the importance of non-stationary SST variability in driving the atmospheric response to ENSO. The strong decadal and multi-decadal signals in latitudinal SST and AAM found in our results suggest the existence of basin-scale modes on these time scales as well [*Vautard and Ghil*, 1989; *Moron et al.*, 1998; *Evans et al.*, 2001], whose origin and dynamics remain to be elucidated.

[13] **Acknowledgments.** Professors Michael Ghil, Raymond Hide and Yuk Yung made insightful comments regarding the work presented here; we acknowledge Dr. T.P. Yunck for valuable comments on this text. SST data were obtained from the NOAA/Climate Diagnostic Center (CDC) on their website (http://www.cdc.noaa.gov); GISST data set are obtained from the JPL Physical Oceanography-Distributed Active Archive Center; belted atmospheric angular momentum was calculated from NCEP reanalysis wind fields, also obtained from the CDC. The work of the authors presents the results of one phase of research carried out at the Jet Propulsion Laboratory, under contract with the National Aeronautics and Space Administration. OdV is a post-doctoral researcher of the Belgian Fonds National de la Recherche Scientifique (National Funds for Scientific Research).

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